DC Energy Storage in the CERTS Microgrid

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Introduction

This report discusses one aspect of energy storage in microgrids. The report specifically addresses the CERTS Microgrid, but the concepts are equally applicable to other microgrid configurations. This report discusses selection of energy storage technology as well as sizing energy storage. These two topics are dealt with in terms of what is commercially viable in 2008. It is understood that, as other technologies advance through the commercialization process, the findings in this report will require revisiting.

The CERTS Microgrid will commonly employ energy storage to fill two different functions. These two functions are:

1. Providing energy for short-term requirements, such as meeting step-load changes in energy demand; and
2. Providing energy for long-term requirements, such as shifting energy demand from on-peak hours to off-peak hours.

The short-term energy storage is required in an isolated microgrid for stable operation. Short-term energy storage will have discharge time durations ranging from milliseconds to a couple tens of seconds. The actual duration will depend on the prime mover being employed in the microgrid. For example, a fuel cell will require energy storage for much longer time periods (on the order of tens of seconds) than will a reciprocating combustion engine (on the order of fractions of a second).

Long-term energy storage is not a requirement for microgrid operation; rather it is an enhancement which will add economic benefit to the microgrid. Long-term storage can be used to shift energy to different times of day, or to shave peaks, to take advantage of economic incentives.

In the CERTS Microgrid the "microsource" is required to be a complete energy supply. That is, a microsource can be added as a complete unit to a microgrid without requiring the addition of other power supply hardware. Thus, the microsource will consist of a prime mover, the energy storage required for that specific prime mover, and the power electronics and controls required for the microsource to perform properly. Short-term energy storage is a <u>required</u> part of the microsource for proper functioning of the microgrid. This storage will typically be connected to the internal dc bus of the microsource. This allows the output inverter to draw its energy supply from either the prime mover or the energy storage, as appropriate.

Long-term energy storage can be connected anywhere in the microgrid that it is convenient, as there is no interdependency between the individual microsources and the long-term energy storage.

Because of the above described difference in interconnection of these two energy storage functions, a short-hand terminology has been adopted to distinguish between them. Since the short-term storage that is required for proper function of any microsource is typically connected to the microsource internal dc bus, this type of storage is referred to as “dc storage”. Since the long-term energy storage that will be utilized for improved economics will be connected to the most convenient place on the microgrid, and that will be an ac connection, this type of storage is referred to as “ac storage”. This report deals strictly with what we have just defined as dc storage. AC storage will be addressed in a future associated report.

Background

One of the basic premises of the CERTS Microgrid project is that a microgrid must not require custom engineering every time an addition or alteration is made to the microgrid. In order to make addition (or removal) of microsources to a microgrid compatible with this premise, it is necessary for each microsource to be a complete, self-contained energy source. This means that the microsource must include everything that is necessary to meet the energy demand of the loads it will serve. Thus, the microsource must incorporate the power source (prime mover) and any energy storage that is required, as well as the complete power electronics and control package required for integration into a microgrid.

Different prime movers will have different requirements for the energy required from the dc storage that will be combined with it to make up a microsource. The specific prime movers selected for the CERTS Microgrid test bed that is operated by American Electric Power (AEP) near their Dolan Test Facility are natural gas-fired internal combustion reciprocating engines furnished by Tecogen. Laboratory and field testing has shown these engines to have very rapid response to load transients. The time required for one of these engines to increase power output from idle to full output is roughly 250msec as shown in figure 1. Different engine operating strategies are envisioned that can reduce this time further, perhaps even eliminating the need for dc storage. In contrast, fuel cells will generally require several tens of seconds to make this same output transition. Because of these differences, the proper selection of energy storage medium will vary depending on the prime mover. This report will deal in detail with the Tecogen prime movers, since these are the units for which we have test data.

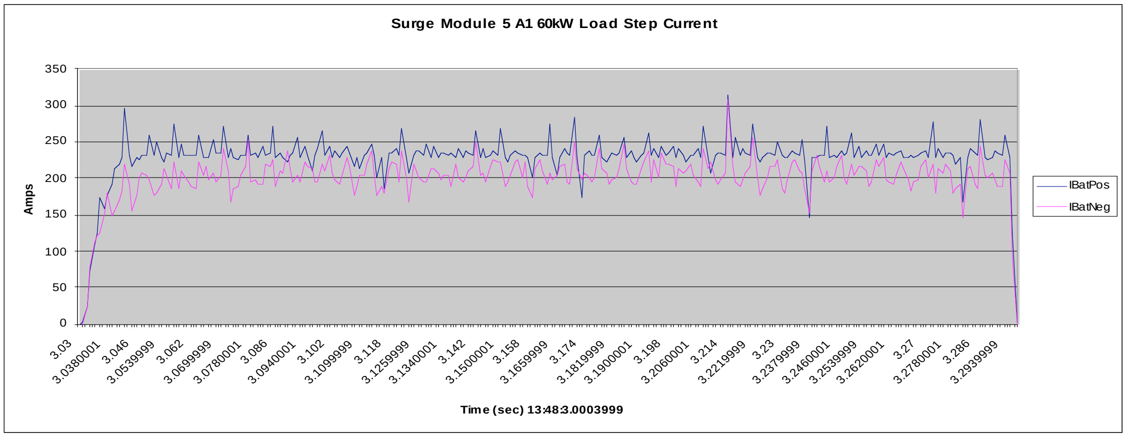


Figure 1 is the current in the surge module for the batteries for Gen-Set A1 from a black start to rated power which is achieved in approximately 250msec.

Technology Selection

The energy storage medium for a commercially installed microsource has the same requirements as all other aspects of a commercial power supply installation. That is, the selected hardware must be robust, should have maintenance requirements that are in line with other hardware at the installation (that is, if all other hardware at the installation can be maintained with twice annual visits, energy storage shouldn't require monthly visits), be readily available in many locations for service purposes, and have a cost that is in line with the benefit added to the installation. With these requirements in mind, the technology selected for the dc storage for the CERTS Microgrid test bed is valve-regulated lead acid (VRLA) batteries. Specifically, absorbed-electrolyte glass mat batteries from MK Batteries were selected. A specification sheet for the selected batteries, which will be referred to throughout this report, is attached at the end of the report.

Other technologies that might be considered for dc energy storage include ultracapacitors, flywheels and chemical batteries employing technologies other than lead acid.

Ultracapacitors appear to hold much promise for the dc storage function in the future as they are ideally suited to discharging large amounts of energy for short periods of time, and they can perform this discharge/charge cycle several orders of magnitude more than a chemical battery can before replacement is required. Although a common perception is that ultracapacitors aren't a commercially viable product today, there are hundreds of thousands of them manufactured each year to fill a market in excess of $250 million. This information, as well as an excellent ultracapacitor technology update, can be found in the November 2007 issue of IEEE Spectrum. This article is available (at the time of this writing) at http://www.spectrum.ieee.org/nov07/5636. This article points out that ultracapacitors are used in myriad niche applications, but the specific product that would translate to the proper storage medium for the dc storage in a microsource has not been developed yet. The above referenced Spectrum article describes research efforts that may change that situation in the near future. Thus, ultracapacitors may be the technology of choice in the not too distant future, but they are not there today.

Flywheels are another promising technology that doesn't yet have an appropriate product for dc storage in microsources. Flywheel developers are focusing their efforts on the market for shifting energy usage, such as peak shaving and moving energy consumption from times of day with high energy rates to those times with low energy rates. These applications require relatively lengthy energy discharge times, with 15 minutes being a minimum, and hours being desirable. The time scale of interest for the microsource dc storage, from fractions of a second to a few tens of seconds, is not currently being addressed by flywheel developers.

Advanced chemical battery technologies, with lithium-ion batteries currently receiving much attention, are in a similar position of not addressing the time periods required for the microsource dc storage application. The greatest interest in advanced chemical batteries is in motive batteries, as are required for electric vehicles. The characteristics for these batteries include a requirement for large amounts of energy (rather than power) to be available over long periods of time. The energy requirement for a microsource dc storage device is small because of the brief amount of time the device is called on to discharge, but the power requirement is relatively large.

The above reasons lead to the selection of lead-acid batteries for the dc storage device in the CERTS Microgrid microsources. The specific choice of VRLA batteries was made to result in battery maintenance scheduling requirements that were compatible with other maintenance requirements of the microsource. Although flooded lead acid batteries would have performed the dc storage function as well as VRLA batteries, their requirement for frequent maintenance resulted in the VRLA battery being a better choice.

Surge Module Operation

Principle operation of a surge module is to provide power to a load increase that the microsource cannot produce instantaneously. Power will continue to be provided by the surge module until the microsource can increase its output power to match the load demand. When the power from the microsource is greater than the load demand then the excess power is used to charge the surge module. Once the surge module becomes fully charged it moves into a standby state until it is needed to provide power. Figure 3 graphically illustrates how the surge module operates during a load step increase.

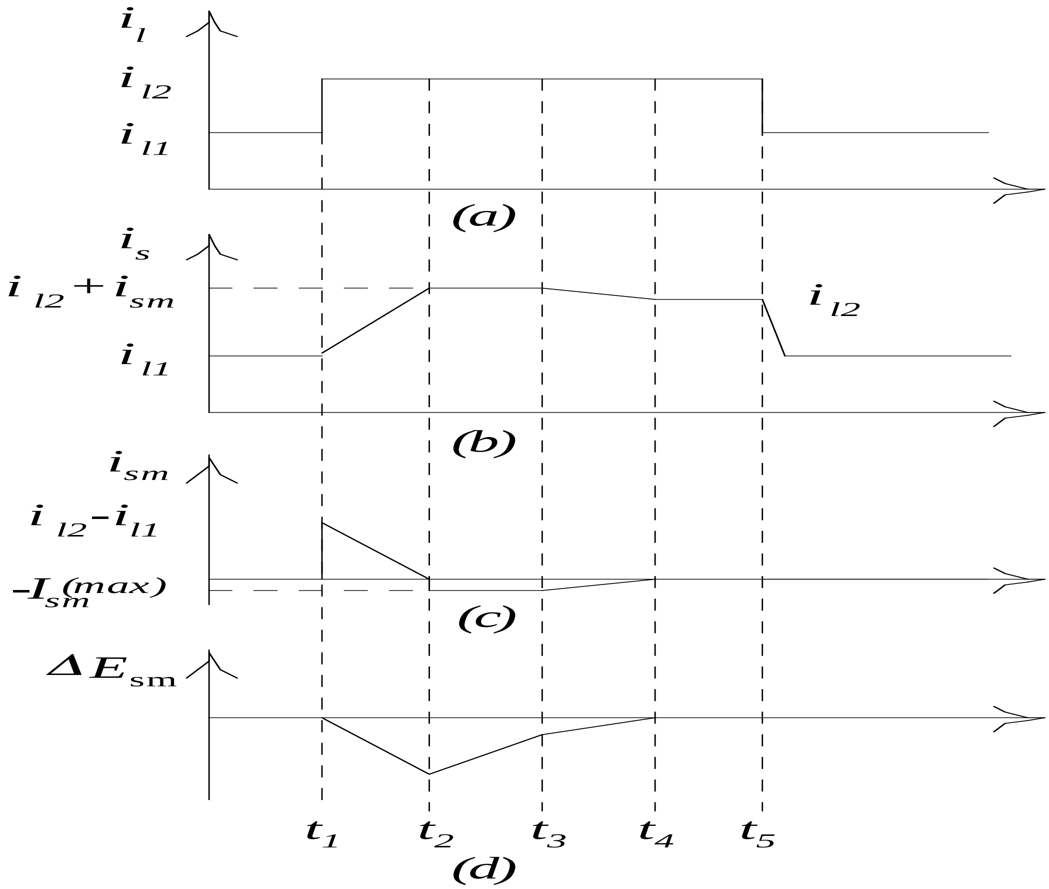


Figure 3: Surge Module operation during a load step increase (a) current demand of the load connected to the microsource (b) dc current supplied by the microsource to the load (c) dc current supplied and absorbed by the surge module; and (d) difference in energy from a fully charge state [2].

Figure 3(a) is the current demanded by the load seen from the inverter. The load is initially consuming current at a magnitude of i_{l1} and then increases at time t_1 to a current magnitude of i_{l2}. Current is reduced back from i_{l2} to i_{l1} at time t_5. Figure 3(b) is the current i_s supplied from the microsource to the load. When the load increases at time t_1, the microsource cannot instantaneously supply enough current therefore it has a ramp rate $R_1 = \frac{di_s}{dt}$ at which it increase until it can supply enough current for the load which happens at time t_2. The current magnitude at time t_2 which is supplied by the microsource is $i_s = i_{l2} + i_{SM}$, where i_{SM} is the current supplied by the surge module. At this point the microsource is supplying all the current to the load and charging the battery. Time t_3 is when the charging current for the surge module tapers off during the final charge stage in the charging cycle until it is fully charged at time t_4. Current magnitude from the microsource at time t_4 is equal to the current magnitude of the load current $i_s = i_{l2}$. As the load decreases to its initial value of current magnitude i_{l1} the microsource decreases at a ramp rate $R_2 = \frac{di_s}{dt}$ which decreases faster than the R_1 ramp rate. Ramp rate depends on the method of how the microsource discharges energy such as the utilization of breaking resistors or heat sinks.

Figure 3(c) is the current i_{SM} supplied and absorbed by the surge module. The surge module is discharged at time t_1 when the load is increased because the microsource has to ramp up to the demanded power level of the load. Discharge current is no longer needed at time t_2 when the microsource has ramped up to supply enough power for the load. Since the surge module has been discharged, it now needs to be charged which begins at time t_2. The microsource provides this charge current on top of the load current which is limited by the surge module max current charge of $-i_{SM}(max)$. The bulk charge cycle for the surge module lasts from time t_2 to time t_3. In the final charge cycle of the surge module which lasts from time t_3 to t_4, the surge module charge current is proportional to the difference in energy ΔE_{SM}. Figure 3(d) is the difference in energy at the surge module. During the discharge cycle, the difference in energy is proportional to the current being supplied by the microsource. Once the discharge cycle is completed at time t_2, the surge module is being charged which the difference in energy is at a rate of $-i_{SM}(max)$. This rate of change for the difference in energy lasts until time t_3 at which the rate of the difference in energy is proportional to the microsource current supplying the load until time t_4.

One equation that determines how much energy needs to be provided by the DC surge module is $\Delta E_{SM}(t_2) = \frac{V_{dc}}{2}(i_{l2} - i_{l1})(t_2 - t_1) = \frac{V_{dc}(i_{l2} - i_{l1})^2}{2R_1}$, where V_{dc} is the DC-link voltage, $R_1 = {(i_{l2} - i_{l1})}/{(t_2 - t_1)}$, $\Delta E_{SM}(t_2)$ is the absolute value of the energy change, i_{l1} is the initial current from the inverter supplying a load at steady state, t_1 is the time at which the load increases or decreases, i_{l2} is the current from the microsource needed for the increase or decrease in load at time t_1, and t_2 is the time at which the surge module is no longer needed to supply or absorb current to satisfy the load change. This equation was developed by Dr. R.H. Lasseter and his student H. Nikkhajoei which describes how to size a surge module for any type of DC technology from an IEEE paper [2].

Tecogen Gen-set Without the Surge Module

A laboratory test performed by TECOGEN showed that the Tecogen engine has a response time fast enough to load changes that the surge module is not required. However, the engine must operate at a fixed speed without the surge module rather than variable speed. Operating the engine at fixed speed costs money in the burning of fuel at low power outputs, therefore the variable speed operation is desired which requires the surge module. When the gen-set is operated under fixed speed there is a minimum speed for each load step to prevent the engine from stalling. The minimum engine speed for a load step of 60kW was 70Hz (2100RPM) and a load step of 30kW required a minimum engine speed of 65Hz (1950RPM). Figure 2 shows the response of the Tecogen under a 0kW - 60kW load step which was performed without the surge module during a Tecogen factory test [1]. The test resulted in figure 2 when the load was applied the unit operating frequency dropped down to 59.7Hz, current increased to 75.3A , grid voltage remained at 277V, and the unit power output level was 58.8kW RMS and steady state was then achieved. If the CERTS microgrid test bed were going to run the engines without a surge module, then it could use the minimum engine speed of 70Hz (2100RPM) to insure that the engine could satisfy an engine rated load step during tests. This is not desired because one aspect of the CERTS microgrid benefits is to reduce the cost of producing electricity by running the generation sources more efficient which the fixed speed higher RPM does not accomplish during low power outputs. Figure 3 and 4 show the result of the Tecogen with the surge module for a 50kW load step from 0kW in variable speed mode. With the surge module online, it can be seen that the load step is a smoother transition compared to the tecogen without the surge module in figure 2. The test resulted in figure 3 when the load was applied the unit operating frequency dropped down to 59.8Hz, current increased to 63.4 , grid voltage remained at 277V, and the unit power output level was 50.97kW RMS and steady state was then achieved. In figure 4, the surge module dc current increases when the step load is applied and remains sourcing current until the engine reaches a certain speed. The Tecogen then increases speed until steady state is achieved.

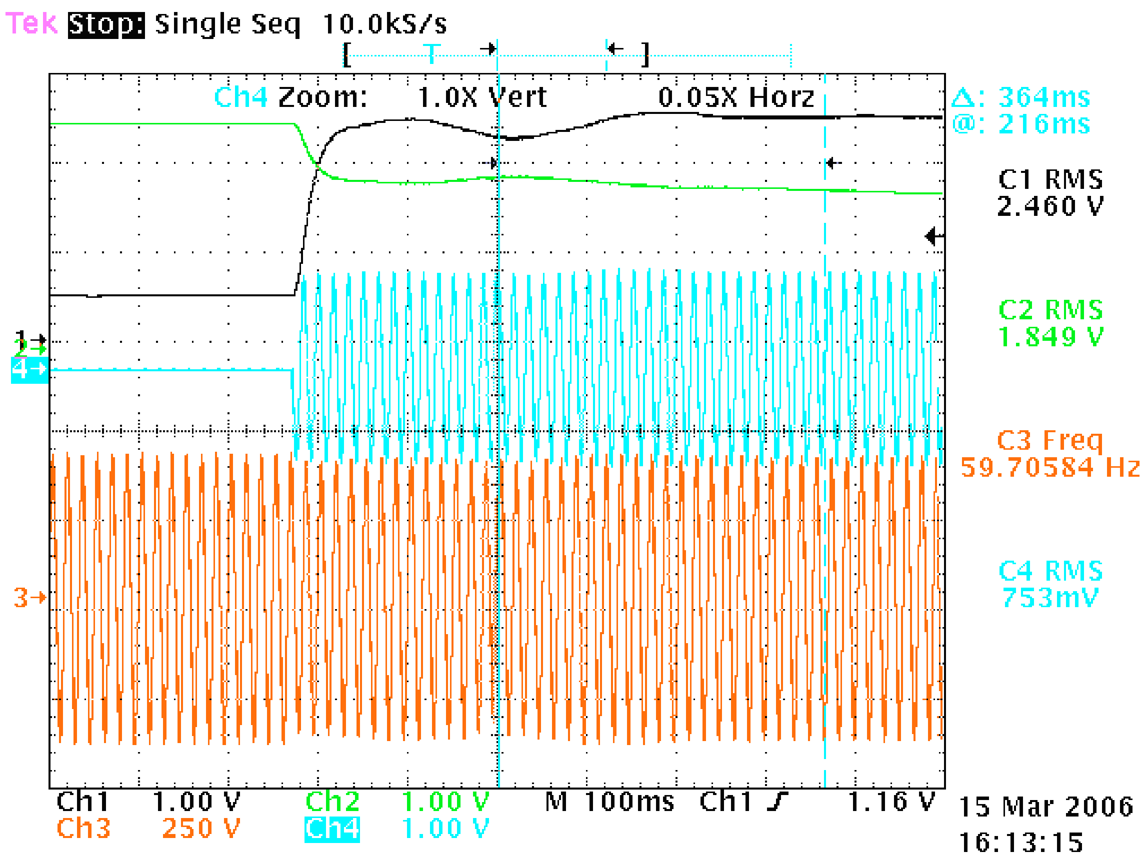


Figure 2 is the response of the Tecogen generator without the surge module for a 60kW load step and a fixed speed of 70Hz (2100RPM). Ch1 is the Unit RMS Power Output, Ch2 is the Unit Operating Frequency, Ch3 is the Grid Voltage L-N (nominal 277 volts), and Ch4 is the Unit Output Current [1].

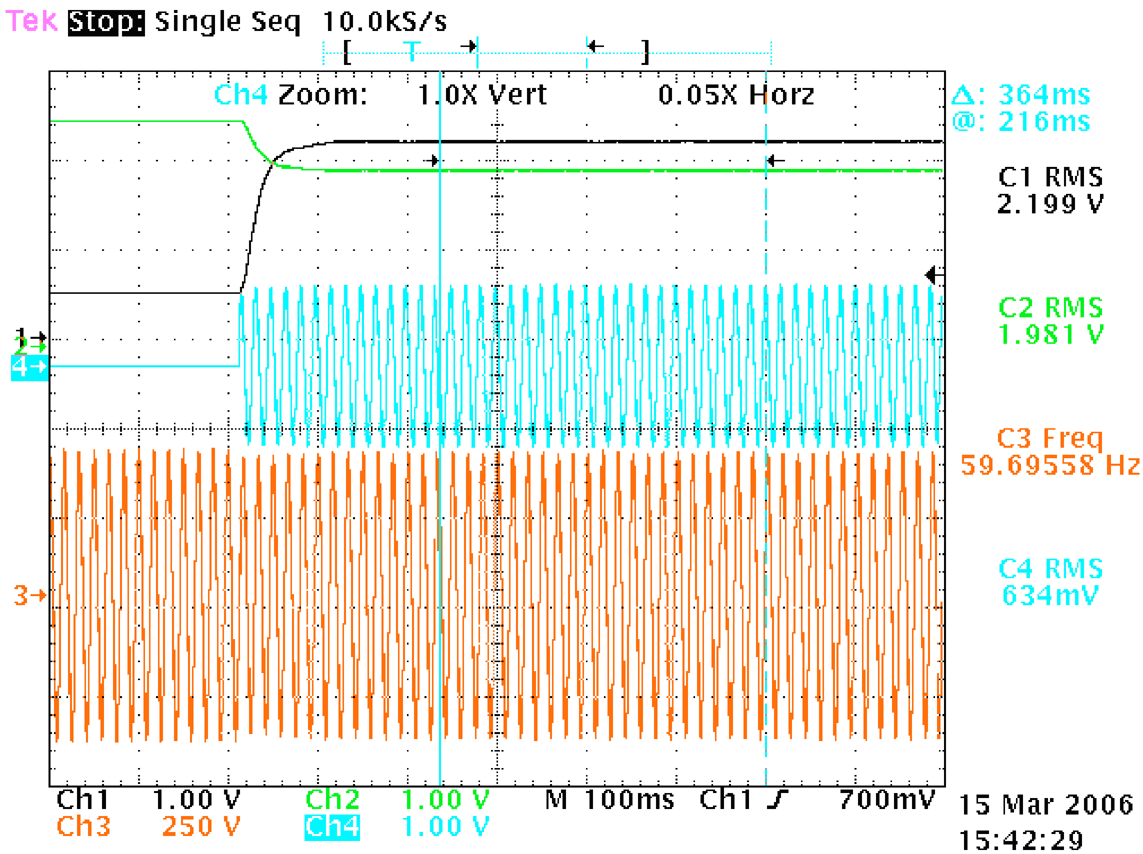


Figure 3 is the response of the Tecogen generator with the surge module for a 50kW load step operating in variable speed mode. Ch1 is the Unit RMS Power Output, Ch2 is the Unit Operating Frequency, Ch3 is the Grid Voltage L-N (nominal 277 volts), and Ch4 is the Unit Output Current [1].

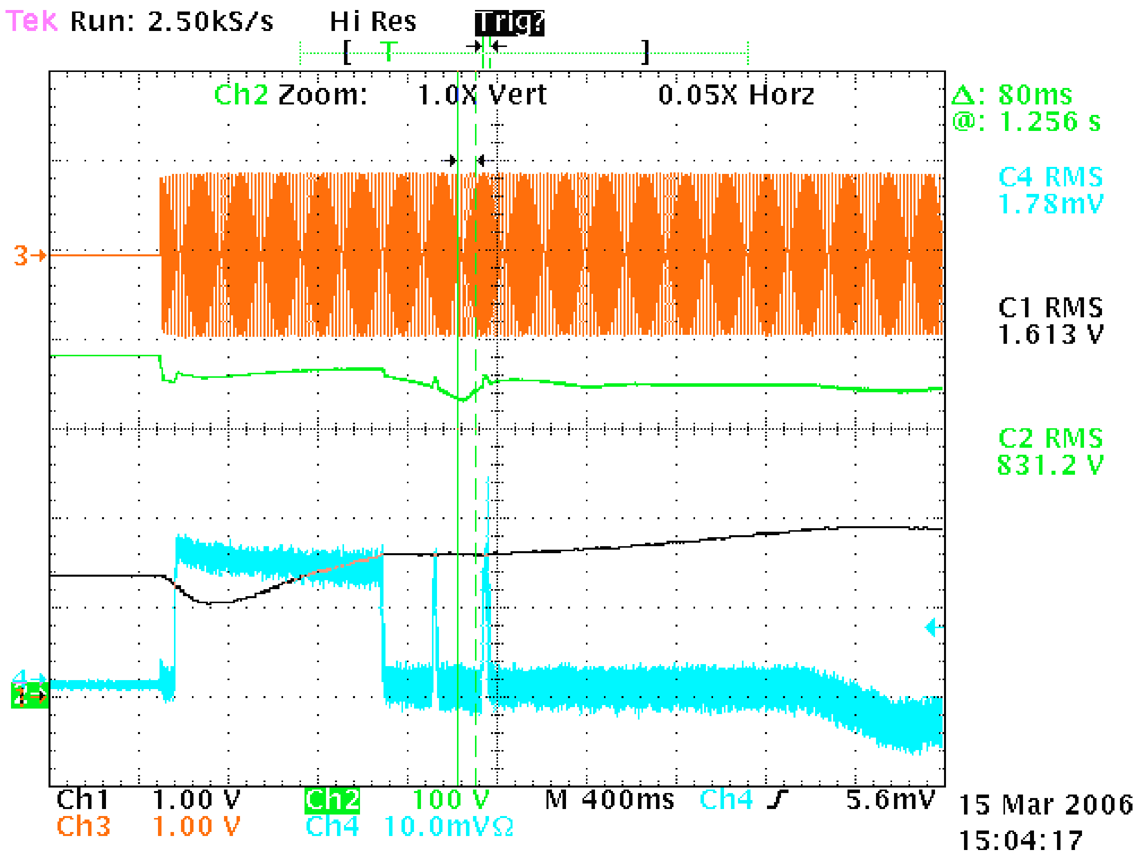


Figure 4 is the response of the Tecogen generator with the surge module for a 50kW load step operating in variable speed mode. Ch1 is the Engine RPM, Ch2 is the Bus Voltage, Ch3 is the AC Current, and Ch4 is the Surge Module DC Current [1].

Sizing Batteries for DC Storage

Batteries are typically thought of as either energy batteries or power batteries. The difference is in the internal construction – mostly plate thickness, which is altered depending on the battery's intended use. An energy battery is typically discharged for time durations of greater than 15 minutes and up to several hours, while a power battery is typically discharged for 30 seconds or less. Automobile batteries, known as SLI (starting, lighting, and ignition) batteries, are probably the best known examples of power batteries. These SLI batteries typically discharge hundreds of amps for a few seconds. SLI batteries are often given a "cold-cranking amps" rating in addition to (or instead of) an amp-hour rating, since the amp-hour rating is not especially meaningful in terms of the SLI application. Construction of a power battery is typified by thin plates, which allows rapid extraction of large amounts of power.

Stationary batteries, as are commonly used for backup power in emergency lighting, substations, and UPS applications, are typical of energy batteries. These energy batteries generally have thicker plates which allow energy to be withdrawn over long periods of time without concern about heat warping the plates as can happen when SLI batteries are discharged over long periods of time.

Conventional battery sizing techniques are biased toward energy batteries. These techniques begin with determining energy requirements for the load. Battery size, in amp-hours, is then determined so that the energy requirements of the load will be met. This conventional technique is not applicable to the power battery required for dc storage in a microsource. Battery sizing for this application is more comparable to battery selection for automotive starting applications. (Note that this refers to the conventional battery used to start a gasoline engine, not the batteries used in an electric vehicle.) The battery should be sized for maximum discharge current for a short (seconds) period of time.

A Battery Sizing Example from the CERTS Microgrid Testbed

Preliminary design studies for the microsources used at the CERTS Microgrid testbed indicated that the maximum discharge current for the dc storage should be 200 amps, and that this current should be available for 250 milliseconds. In order to help clarify the issue of battery sizing by maximum discharge current rather than by energy need, a brief discussion using the specifics of the CERTS Microgrid testbed follows.

An important concept in battery selection is that the amp-hour rating of a battery is discharge-rate specific. The greater the discharge rate, the less energy can be withdrawn from a specific battery. Referring to the battery specification sheet from MK Batteries for the ES10-12S battery (the battery used for dc storage at the CERTS Microgrid testbed) at the end of this report, it can be seen that this battery is rated for 10 amp-hours at the 20 hour rate, 8.5 amp-hours at the 5 hour rate, 4.5 amp-hours at the 1 hour rate, and 3.5 amp-hours at the 20 minute rate. (Note that the 1 hour rate is designate "1C", meaning 1 times the 10 hour rate, or 10 amps. Thus the 1C rating is the 1 hour rate. The 20 minute rate is designated "3C", meaning 3 times the 10 hour rate, or 30 amps.) This reduction in amp-hour (Ah) capacity with increased discharge current is the first indicator that a high current discharge, such as 200 amps, will not result in an energy capacity, or Ah capacity, that has much correlation to the battery's rated capacity.

The ES10-12S battery specification sheet also includes information that can be used for battery selection for high-discharge rate applications. Note that about one-third of the way down the left-hand column, there are two "Maximum Discharge Current" values – one for a 5-second discharge and one for a 30-second discharge. Recalling from above, the expected maximum discharge current requirement for this application was 200 amps. Note from the specification sheet that the ES10-12S battery can supply 200 amps for 30 seconds. Also note that it can supply 400 amps for 5 seconds. Since the expected maximum discharge current was 200 amps, and this current would be required for only 250 milliseconds, the ES10-12S battery appears to be a very conservative selection. This conservative selection was a deliberate decision based on the fact that this was an experimental installation, and it was decided that a conservative approach should be taken.

Further Refining the Battery Selection Process

The table of battery characteristics for 12 volt MK Batteries at the end of this report can be used to illustrate the selection process that would be used today, now that experimental evidence has substantiated the design predictions for required discharge rate and duration. This table can also be used to further illustrate the error in trying to select a battery for high discharge-rate applications using amp-hour capacity, rather than maximum discharge current.

If one were to try to size the dc storage battery for the CERTS Microgrid testbed using required energy capacity, the beginning point would be to calculate the energy required for a single discharge. This is 200 amps for .25 seconds, or roughly 0.014Ah. One would then decide how many discharges in succession the battery must be capable of prior to being recharged. We'll select ten discharges for this example. That means we need a battery with 0.14Ah capacity. Referring to the MK Batteries table at the end of this report, it can be seen that the smallest battery in the table, the ES0.8-12, is rated for 0.595Ah at the 5 hour rate – apparently significantly more capacity than is required. However, reference to the "Maximum Discharge Current (A) for 5 sec." column indicates that the maximum discharge current is only 28 amps – significantly less than the required 200 amps.

The correct way to use this table for selection of a high discharge-rate application is to simply look at the "Maximum Discharge Current (A) for 5 sec." column, and find a value of at least 200 amps. The ES5-12 battery meets this requirement, and is the correct battery to use. Note that this is a substantially smaller battery than the ES10-12 that was originally selected, having one-half the Ah capacity, weighing about 4.0 pounds, as opposed to 7.3 pounds, and having reduced physical size. These are all benefits to the overall microsource because they will result in a less expensive installation that requires less physical space.

Details of the CERTS Microgrid Testbed DC Storage Installation

The dc storage requirement for the CERTS Microgrid testbed was satisfied by supplying each microsource with a "Surge Module". This Surge Module consists of a battery bank and the necessary power electronics to charge and discharge the battery. The Surge Module is connected to the power source at the internal dc bus that is between the generator dc output and the inverter used to convert the output power to utility-compatible ac. In the CERTS Microgrid testbed, the Surge Module is the dc storage.

The remainder of this report discusses lessons learned with the original Surge Modules as well as making recommendations for dc energy storage for future applications.

<u>The Original Configuration</u> – The Surge Module used in the microsources for the CERTS Microgrid testbed consists of 16 lead acid batteries for each power source. These are 12-volt valve-regulated (also known as "maintenance free") batteries of the type that are often used as motorcycle starting batteries. The batteries are connected in a center-tapped arrangement with 8 batteries on the positive side and 8 on the negative side of neutral,

resulting in nominally ±96 volts dc. This is then converted to ±450 volts dc in order to be compatible with the microsource's dc bus.

The battery bank is in a tray in the bottom of the Surge Module. The remainder of the Surge Module contains the power electronics required to boost the battery voltage to ±450 volts dc (a boost converter) and to charge the battery bank (a buck converter). The complete Surge Module, which measures 30" high by 30" wide by 13" deep, is wall mounted beside each individual prime mover.

The boost converter in each Surge Module has a maximum current limit of 200 amps and limits the power output to 20kW. This boost converter is currently programmed to discharge the Surge Module for 250 msec when output current increases by a set amount for 2 cycles. This discharge time can be altered to be appropriate for the prime-mover being used. That is, for the Tecogen internal combustion reciprocating engine, which has relatively fast demand response, 250msec is ample time for the engine to ramp up for load increases. However, if the prime mover were a slower responding device, such as a microturbine or fuel cell, then the Surge Module would be reprogrammed to give a longer discharge time, such as 10 or 20 seconds.

The discharge is performed by sending 20kW to the internal bus, or the amount of energy necessary to regulate the bus voltage to ±450Vdc (whichever is less). Thus, the discharge power will typically taper during the discharge period as the prime-mover output increases and the amount of power required from the Surge Module is decreased to maintain ±450Vdc.

The Surge Module also contains a buck converter that is used for charging the batteries. Charging is performed over a significantly longer period of time than discharging, so less current capacity is required. The buck converter has a maximum current capacity of 70 amps, and regulates the battery bus to ±110Vdc (8 batteries at 13.8volts).

The battery banks were each supplied with thermal protection. This consisted of 4 thermal switches, attached to the tops of selected cells, which were intended to turn off the Surge Module when any battery reached 130ºF. This was to protect the battery bank from thermal damage. This strategy will be discussed in some detail below.

Lessons Learned from the CERTS Microgrid Testbed

During the commissioning testing of the microsources, several of the batteries in the Surge Modules were thermally damaged. This appears to be because of prolonged cycling of the Surge Modules. That is, the Surge Modules were discharged, then recharged, then discharged numerous times over a period of several hours while performing the commissioning tests. This would have two effects. The batteries would not have time to cool off between discharges, so they would continually get hotter. Also, they would continually be discharged without being fully recharged. Testing of the batteries following this event showed that most of the individual batteries had been damaged and had to be replaced.

Because of visible evidence of thermal damage to the batteries, an initial reaction to these events was to improve air circulation to the batteries. It was assumed that this would have allowed the batteries to dissipate their heat more effectively, thus avoiding thermal damage. Further investigation showed that this was not needed. Although the air circulation around the batteries is poor, battery heating during normal operation is minimal because of the very brief discharge time, and heat dissipation is not an issue. A test performed specifically to quantify this effect showed that 9 discharges spread over about an hour resulted in temperature rise of the battery terminals of less than 5ºF. The reason battery heating had caused a problem during this testing was the large number of rapid discharges mentioned above – an abnormal situation.

This event also resulted in closer examination of the thermal switch implementation. The thermal switches were intended to ensure that, in an abnormal situation such as this, the Surge Module would be shut down to protect the batteries from thermal damage. For reasons that will be described below, this thermal protection system failed to function properly.

Two techniques are recommended for avoiding this type of battery damage in the future. One technique is to program the software to limit the number of discharges possible in an hour, or some other unit of time as is appropriate for the specific system design. Since each discharge is very brief, very little battery heating is experienced with each discharge. Thus, if battery discharges are limited to no more than, for example, nine per hour, then overheating of the batteries will be avoided. As previously mentioned, testing showed that, for the system used in the CERTS Microgrid test bed, nine discharges in a one-hour period resulted in less than 5ºF battery temperature rise. Although this approach of limiting discharges in a given time period is probably an effective method, the technique was not employed at the CERTS Microgrid test bed.

The technique that was employed is improved battery temperature monitoring, along with appropriate response to elevated battery temperature. In the initial design, the battery temperatures were monitored by placing a thermal switch on the top of 4 selected cells in each of the three Surge Module battery banks. These thermal switches were calibrated for 130ºF, at which point the thermal switches would disable the Surge Module.

Two improvements were made on this technique. First, it was realized that the top of the batteries was a "secondary" cover, and there was only a dead air space below it, followed by the actual battery cover. In other words, the top of the batteries was effectively thermally insulated from the interior of the battery. More effective temperature monitoring can be accomplished by placing the temperature sensors either on a battery terminal, or on the side of the battery. This latter placement assumes that electrolyte is directly in contact with the inner surface of the side of the battery case where the sensor is attached.

Many in the battery industry recommend temperature monitoring from a battery's negative terminal. This is because the terminals are directly connected to the plates, giving a metallic pathway, a good thermal conductor, to the inside of the battery. The negative terminal is recommended because standard battery configuration has one more negative plate than positive. Thus, the negative terminal has a slight edge in providing good internal battery temperature information. Using the negative terminal is not a major issue and, if there is some reason that positive terminals are more readily accessible, they will work just fine. When measuring temperature from battery terminals, it is important to address isolation issues, both from the standpoint of battery voltage isolation and electrical noise isolation.

A second reason to use a battery terminal for thermal measurement, rather than the side of the battery, is that the specific batteries used in the Surge Modules are VRLA (valve-regulated, lead-acid) batteries. These batteries are not filled with electrolyte to the point that one can be certain that there is electrolyte touching any given inner surface of the battery case. Additionally, as the battery ages any electrolyte that may have originally been in contact with the battery case often pulls away from the case. Thus, a side-of-case measurement may give good results early in the battery's life, but then become unreliable as the battery ages.

The battery manufacturer's specification sheet (attached) recommended a maximum operating temperature of 104ºF (40ºC, which is a commonly recommended maximum operating temperature to avoid battery damage), rather than the 130ºF we had initially used.

The final configuration for battery thermal protection at the CERTS Microgrid test bed is to use 4 resistive thermal devices (RTDs) on each Surge Module battery bank. Two of these RTDs are on negative terminals and two are sandwiched between batteries, attached to the battery sides about midway between top and bottom. The relation between the terminal temperatures and the cell-side temperatures will be observed during the duration of the testing.

The RTD readings are fed to a Modbus RTD thermal monitoring module, which includes a capability for alarm settings and for making the temperature readings available to the data acquisition system. The resulting battery temperatures are collected by the data acquisition system to allow observation of operating temperatures during the full system tests at the test bed. The software has been modified to disable Surge Module discharge if any on the thermocouples shows a temperature in excess of 104ºF (40ºC).

Initial readings from this temperature monitoring system indicate 6 or 7 discharges in an hour result in a brief temperature rise of less than 5ºF, which stabilizes to a 1 or 2ºF steady-state rise.

Recommendations

The Surge Module as initially designed for the CERTS Microgrid test bed is a reasonable design that functions well. The specific battery selected for this application is a good choice, although money and space can be saved in the future by using a smaller battery.

The choice of battery temperature monitoring techniques, which allowed thermal damage to most of the batteries, is the only clear shortcoming of this design. The modifications described above, and summarized below, will assure thermal protection for the batteries in the future.

Also, a technique for predicting battery end-of-life is desirable. As with many maintenance operations, it is best to replace the batteries before they fail, rather than waiting for failure and the associated additional costs that failure during operation can bring. A technique for predicting battery end-of-life will be discussed.

- Temperature monitoring

As described above, it is important in temperature monitoring that the internal battery temperature is actually accessed. Measuring the temperature of the top of the battery is not an effective way to measure a battery's internal temperature. The preferred method is to measure the temperature of a negative battery terminal. An alternative method is to measure the side of the battery case, with the measurement being taken well below the level of the electrolyte inside the battery. With flooded batteries, this is relatively effective. With valve-regulated batteries (also known as "starved electrolyte", gel-cell, AGM, or "maintenance free" batteries), measuring the side of the battery may not give consistent results as the electrolyte may not be in contact with the inside of the battery case at the point where the temperature monitor is attached. Even in those cases where the electrolyte is initially in contact with the inside of the battery case at the attachment point, this can change as the electrolyte shrinks during battery operation. Thus, for valve-regulated batteries, a battery terminal is always the preferred temperature measurement point.

Care should be taken when temperature measurements are obtained from battery terminals to isolate both electrical noise and battery voltage from the instrumentation.

Note that battery temperature reaching an upper limit is clearly an indicator of other problems in the system, since the batteries normally only operate for very short periods of time, which doesn't generate enough heat to cause thermal problems. Typically, the batteries would never discharge for more than 60 total seconds out of an hour. Thus, high battery temperature needs to be noted in order to initiate a trouble-shooting procedure. At a minimum, an alarm should be activated when the battery reaches the maximum operating temperature as recommended by the battery manufacturer. If the maximum operating temperature is not available from the manufacturer, then 40ºC (104ºF) should be used. Additional protection of the batteries may be desired, in which case shut-down of the Surge Module can be initiated at 40ºC. Also, it may be desirable to use data logging to follow battery temperature trends.

- Predicting battery end-of-life

Being able to predict the end-of-life of a battery is an important economic consideration for a battery system that is supporting critical loads, as is the case with the Surge Module in the CERTS Microgrid. It is far superior to replace a battery as it nears end-of-life than to wait until battery failure to replace it. A straight-forward method for predicting battery end-of-life is to count the amp-hours out of the battery.

Battery manufacturers often include “Life Expectancy” data on their specification sheets. On the attached spec sheet for the ES10-12S Surge Module batteries, this can be seen near the bottom of the left hand column. Note that the data provided can be converted into amp-hours out of the battery. For example, 100% depth of discharge (that is, the battery energy storage is completely utilized each discharge/charge cycle) results in 200 cycles. Since the nominal battery capacity is 10Ah, this is the equivalent of 2000Ah total battery discharge. Also note that at 50% depth of discharge the cycle life is given as 500 cycles. That is, 5Ah for 500 cycles, which is 2500Ah. This reflects the fact that the more deeply a battery is discharged, the shorter its cycle life will be. This life expectancy data can be used to indicate when battery end-of-life is being reached.

If an installation employs data monitoring, then the data required to predict battery end-of-life can be acquired by accumulating amp hours discharged from the battery. Note that the amp hours recharged back to the battery should not be used in this particular data set. Simply accumulate amp hours discharged and send an alarm when the critical value, such as 2500, has been reached. Note that, since the specific values for percent discharge, and the discharge rate, used in the Surge Module are significantly different than the values given in the specification sheet, or than rates the battery is conventionally expected to see, it is worthwhile to contact the manufacturer to obtain a life expectancy value under the specific conditions that the battery will be seeing.

MK Batteries Specification Sheet for CERTS Microgrid DC Storage Batteries

ES10-12S

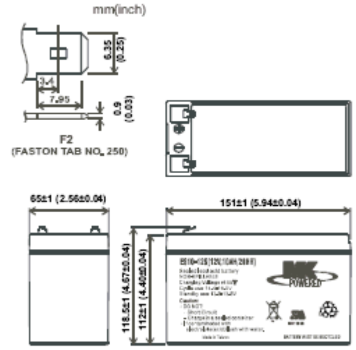
Maintenance-Free Rechargeable Sealed Lead-Acid Battery

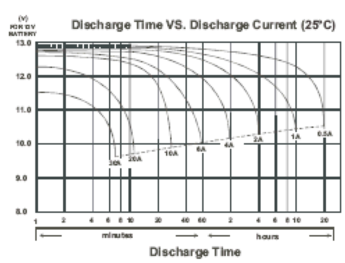
SPECIFICATIONS

Nominal Voltage (V)	12V
Nominal Capacity	
20hour rate (0.5A to 10.50V)	10Ah
10hour rate (1A to 10.50V)	10Ah
5hour rate (1.7A to 10.20V)	8.5Ah
1C (10A to 9.60V)	4.5Ah
3C (30A to 9.60V)	3.5Ah
Weight	7.34 Lbs. (3.33 kg)
Internal Resistance (at 1KHz)	15 mΩ
Maximum Discharge Current for 30 seconds :	200A
Maximum Discharge Current for 5 seconds :	400A
Operating Temperature Range	
Charge	0°C(32°F) to 40°C (104°F)
Discharge	-15°C(5°F) to 50°C (122°F)
Storage	-15°C(5°F) to 40°C (104°F)
Charge Retention (shelf life) at 20°C (68°F)	
1 month	92%
3 month	90%
6 month	80%
Charging Methods at 25°C (77°F)	
Cycle use :	Charging Voltage 14.4 to 15.0V Maximum Charging Current 3A
Standby use :	Float Charging Voltage 13.50 to 13.80V No current limit required
Life expectancy :	
Cycle Use :	100% depth of discharge 200 cycles 80% depth of discharge 225 cycles 50% depth of discharge 500 cycles
Standby Use :	3~5 years
Case Material	ABS (Option: 94-HB & 94V-0 flame retardant case)
Terminal	F2

DIMENSIONS

mm(inch)





MK Battery
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MK Batteries
Table of Battery Characteristics

12V BATTERIES

		Nominal Capacity (AH)			Weight		Terminal		Dimensions (Inch)				Dimensions (mm)					
Model	Nominal Voltage (V)	20hr Rate F.V. (1.75V/cell)	10hr Rate F.V. (1.75V/cell)	5hr Rate F.V. (1.75V/cell)	g.	lbs.	Type	Position	L	W	H	TH	L	W	H	TH	Maximum Discharge Current (A) for 5 sec.	Maximum Charge Current (A)
ES0.8-12	12	0.7	0.665	0.595	370	0.82	WIRE(w60-10)	15	3.78	0.98	2.44	2.44	96	25	62	62	28	0.21
ES1.2-12	12	1.2	1.14	1.02	596	1.31	F1	4	3.82	1.69	2.09	2.32	97	43	53	59	48	0.36
ES1.9-12	12	2.3	2.185	1.96	1060	2.34	F1	2	7.01	1.34	2.36	2.60	178	34	60	66	92	0.69
ES2-12SLM	12	2	1.9	1.7	762	1.68	F1	12	5.91	0.79	3.54	3.54	150	21	90	90	72	0.54
ES2.3-12V	12	2.1	1.9	1.785	682	1.50	F13	16	7.17	0.91	2.40	2.40	182	23	61	61	20	0.69
ES2.9-12	12	2.9	2.755	2.465	1263	2.79	F1	13	3.11	2.20	3.90	4.21	79	56	99	107	116	0.87
ES3-12	12	3	2.85	2.55	1370	3.02	F1	4	5.28	2.64	2.34	2.58	134	67	60	66	120	0.90
ES3-12R	12	2.8	2.66	2.4	1160	2.55	F1	2	5.24	1.30	3.82	4.09	133	33	97	104	112	0.84
ES5-12*	12	5	4.75	4.25	1830	4.04	F1, F2	3	3.54	2.76	4.00	4.25	90	70	101	108	200	1.50
ES7-12*	12	7.2	6.84	6.12	2678	5.91	F1, F2	5	5.94	2.56	3.70	4.02	151	65	94	102	288	2.16
ES9-12	12	9	8.55	7.65	2980	6.56	F2	5	5.94	2.56	3.70	4.02	151	65	94	102	360	2.70
ES10-12S	12	10	9.5	8.5	3335	7.34	F2	5	5.94	2.56	4.41	4.65	151	65	112	118	400	3.00
ES12-12	12	12	11.4	10.2	4270	9.39	F2	5	5.94	3.86	3.66	3.86	151	98	93	98	480	3.60
ES12-12TE	12	12	11.4	10.2	3930	8.65	F3	5	5.94	3.86	3.66	4.06	151	98	93	103	480	3.60
ES17-12	12	18	17.1	15.3	6283	13.82	F2, F3	17	7.13	2.99	6.57	6.57	181	76	167	167	720	5.40
ES20-12C	12	20	19	17.0	6600	14.55	F3	10	7.13	2.99	6.54	6.54	181	76	166	166	300	6.00
ES26-12	12	26	24.7	22.1	9327	20.52	F2, F3	17	6.54	6.89	4.92	4.92	166	175	125	125	1040	7.80
ES33-12	12	34	32.3	28.9	11107	24.44	F4	9	7.76	5.16	6.26	7.09	197	131	159	180	1360	10.20
ES40-12	12	45	42.75	38.25	14109	31.04	F4	10	7.80	6.54	6.73	6.73	198	166	171	171	1800	13.50
ES40-12HR	12	37	35.15	31.45	14640	32.28	F9	11	9.84	3.84	7.95	7.95	250	98	202	202	1480	11.10
ES50-12	12	50	47.5	42.5	14237	31.32	F8	11	7.80	6.54	6.73	6.73	198	166	171	171	1000	15.00

REFERENCES

[1] Tecogen Factory Testing, 03/15/2006, “TECOGEN 60kW Inverter-Based CHP Modules”, CERTS Microgrid Test Bed Project

[2] Nikkhajoei, H., Lasseter, R.H., *“Distributed Generation Interface to the CERTS Microgrid”*, IEEE Transactions on Power Delivery, Volume 24, Issue 3, July 2009, pages 1598-1608